NACA

RESEARCH MEMORANDUM

INVESTIGATION OF SEVERAL CLAMSHELL VARIABLE-AREA

EXHAUST NOZZLES FOR TURBOJET ENGINES

By Bruce T. Lundin

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS
WASHINGTON

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

INVESTIGATION OF SEVERAL CLAMSHELL VARIABLE-AREA

EXHAUST NOZZLES FOR TURBOJET ENGINES

By Bruce T. Lundin

SUMMARY

The results of several investigations of the performance of different types of clamshell variable-area exhaust nozzle for turbojet engines conducted to determine the efficiency of this type of exhaust nozzle as compared with the conventional fixed-area conical exhaust nozzles are presented. These investigations were conducted at zero-ram sea-level conditions on three different full-scale turbojet engines. The performance of five different nozzles, two of which were designed for operation on an afterburner tail pipe, is presented. In addition to the nozzle efficiency, as determined from jet-thrust performance, the mechanical reliability of the nozzles and the use of various gas sealing devices are discussed.

The clamshell-type variable-area nozzle was found to have satisfactory mechanical reliability even after operating under afterburning conditions for about 40 minutes. Thrust losses due to gas leakage under the movable flaps of the nozzle were eliminated by proper sealing devices. With three of the variable-area nozzles investigated, one of which provided an area-variation ratio of about 1.86, the jet thrust was within 0 to $1\frac{1}{2}$ percent of that obtained with conventional fixed-area nozzles. The other two nozzles investigated resulted in thrust losses of about 4 and 8 percent; the cause of the loss in thrust for these two nozzles is principally attributed to a nonplanar outlet configuration formed by the nozzle flaps.

INTRODUCTION

The application of tail-pipe burning as a thrust-augmentation method for turbojet engines requires the use of a variable-area exhaust nozzle in order to provide efficacious engine operation under both normal and augmented conditions. The amount of thrust

augmentation obtained by water or water-alcohol injection may also
be considerably increased on many types of turbojet engine by the
use of a variable-area exhaust nozzle because of the independent
control of turbine gas temperature and engine speed that the nozzle
provides. For turbojet engines not equipped with thrust-augmentation
devices, the proper adjustment of the area of the exhaust nozzle may
also provide improvements in specific fuel consumption at reduced
thrust outputs, a considerable degree of thrust regulation at con-
stant engine speed, and improved starting characteristics.

A variable-area nozzle of the clamshell type, which consists
essentially of two movable spherical segments or flaps that rotate
over an inner fixed section, was designed and used on a turbojet
engine at the NACA Cleveland laboratory (now the Lewis laboratory)
in 1943; the results of an investigation of the efficiency of this
nozzle are reported in reference 1. Following the satisfactory
results of this investigation, variable-area exhaust nozzles of
this type came into general use for many research investigations,
particularly in the field of thrust augmentation. An investiga-
tion of standard engine performance with a variable-area exhaust
nozzle at various altitude conditions, including an evaluation of
the efficiency of the nozzle used, is reported in reference 2.

Because many of the nozzles that were used in subsequent inves-
tigations incorporated different design features or were operated on
different types of engine than the nozzles reported in references 1
and 2, the performance of these various nozzles was investigated from
time to time. The results of several of these investigations, which
were conducted at the NACA Lewis laboratory on full-scale turbojet
engines at sea-level zero-ram conditions, are reported herein. The
performance of five different variable-area exhaust nozzles are
reported; three different engines were used, one of which was alter-
natively equipped with a standard and an afterburner tail pipe. The
efficiency of each variable-area nozzle is compared with that of
various fixed-area conical nozzles over a range of engine operating
conditions. The mechanical reliability of the nozzles and the use
of various sealing devices between the movable flaps and the fixed
inner section of the nozzle are also discussed. An illustration of
the effect of variable-exhaust-nozzle area on the specific fuel con-
sumption and thrust regulation of a turbojet engine not equipped
with thrust-augmentation devices is also presented.

APPARATUS

Nozzles. - Five variable-area exhaust nozzles of the clamshell
type were investigated. This type of nozzle (fig. 1) consists of

two movable flaps shaped like spherical segments that rotate over a fixed inner section having either a spherical zone or a straight cylindrical outlet.

The flaps are hinged on pivot shafts on the sides of the nozzle and connected to a linkage system in such a manner than an actuating force moves both flaps simultaneously over the inner section of the nozzle. The pivot shafts are so located at the center of curvature of the movable flaps that the actuating force is not opposed by gas-pressure forces but only by the friction of the moving parts. As shown in figure 1, the projected outlet area formed by the nozzle flaps in the closed position is that of an ellipse; in the open position, the projected outlet area of the nozzle may be either elliptical or circular depending on the amount the nozzle flaps are permitted to open. In addition to this elliptical outlet area, the angle formed between the edges of the nozzle flaps in the closed position is less than 180° and results in a nonplanar configuration of the nozzle outlet. The shape of both the outlet ellipse and the nonplanar outlet configuration of the nozzle in the closed position is used to describe the geometrical design features of the various nozzles investigated. The shape of the outlet ellipse is specified by the ratio of the major axis to the minor axis, or the ratio a/b (fig. 1), and the nonplanar outlet configuration is specified by the ratio of the transverse projected outlet area to the longitudinal projected outlet area, or the area ratio A/B (fig. 1). These geometrical features and other principal dimensions of the five variable-area nozzles investigated for both the open and closed position are summarized in the following table:

| variable-area nozzle | Nozzle position | | | | | | Major axis Minor axis a/b (closed) | Ratio of transverse to longitudinal area A/B (closed) |
| | Open | | | Closed | | | | |
	Major axis (in.)	Minor axis (in.)	Equivalent diam. (in.)	Major axis (in.)	Minor axis (in.)	Equivalent diam. (in.)		
1	13.0	13.0	13.0	12.6	10.5	11.5	1.20	0.08
2	19.9	18.1	19.0	17.6	15.4	16.5	1.14	.10
3	21.0	21.0	21.0	21.0	15.5	18.0	1.35	.13
4	25.0	19.4	22.0	25.0	8.5	14.6	2.94	.25
5	24.2	18.9	21.4	18.9	14.0	16.2	1.35	.06

Additional detailed design features of the various variable-area nozzles are subsequently described. Straight-sided, fixed-area conical nozzles having cone angles varying from 15° to 30° were used to obtain comparative engine performance for evaluation of the variable-area nozzles.

Experimental setup. - Three different turbojet engines were used: a 1600-pound- and a 4000-pound-thrust centrifugal-flow-compressor engine and a 4000-pound-thrust axial-flow-compressor engine. A different variable-area nozzle (nozzles 1, 2, and 3) was investigated on each engine with standard tail pipes. Variable-area nozzles 4 and 5 were investigated on the 4000-pound-thrust axial-flow-compressor engine with an afterburner tail pipe.

The investigations were conducted on various zero-ram sea-level test stands, which differed in small details but, in general, were of the type shown in figure 2. The engine was rigidly mounted on a frame that was suspended from the ceiling of the test cell by four rods that swing on ball-bearing pivots. Lateral restraint was provided by guide rollers; longitudinal restraint was provided by the thrust-measuring device. All instrumentation and control lines were flexible and a special seal (detail in fig. 2) was installed where the tail pipe passes through the wall of the cell in order to permit axial movement of the engine without excessive air leakage around the tail pipe.

The engine thrust was transmitted through a linkage to the diaphragm of an air-pressure cell. A pilot valve, directly connected to the thrust linkage, controlled the air pressure in the diaphragm cell to balance the thrust force. The thrust was read from a manometer connected to the diaphragm cell. The thrust device was calibrated by means of dead weights. The air supply to the engine entered the nearly airtight test cell through air-measuring nozzles. The engine fuel (kerosene) flow was measured with calibrated rotameters. For all the variable-area nozzles investigated, pressures and temperatures were measured at the engine inlet, the compressor outlet, and the turbine outlet by conventional instrumentation. For variable-area nozzles 3, 4, and 5, additional instrumentation was installed to measure the condition of the gas upstream of the exhaust nozzle. For nozzle 3, this instrumentation was as follows:

(1) Eight strut-type thermocouples located 4 inches in from the tail-pipe wall and 2 inches upstream of the exhaust-nozzle; the exhaust-nozzle inlet is considered as the point where contraction begins

(2) One rake of 11 total-pressure tubes spaced on centers of equal area and located 1 foot upstream of the exhaust-nozzle inlet

For nozzles 4 and 5, the exhaust-nozzle-inlet instrumentation was as follows:

(1) Two rakes of 10 thermocouples each located on a single diameter 16 inches upstream of the exhaust-nozzle inlet; constant thermocouple spacing of $1\frac{1}{4}$ inches

(2) Two rakes of 10 total-pressure tubes each located and installed the same as the thermocouple rakes

PROCEDURE

Runs were made on each engine at zero-ram sea-level conditions over a range of engine speeds for various fixed-area conical nozzles and for various positions of the variable-area nozzle. These conditions are listed in the following table:

Variable-area nozzle	Rated engine thrust (lb)	Compressor	Speed range (percent normal rated)	Fixed-area nozzle diameter used for comparison (in.)
1	1600	Centrifugal flow	85-100	$11\frac{1}{2}$ - 13
2	4000	Axial flow	52-100	16 - $17\frac{3}{4}$
3	4000	Centrifugal flow	75-100	18 - 21
4,5	[a]4000	Axial flow	70-100	$16\frac{1}{4}$ - 18

[a]With afterburner tail pipe.

The performance data reported for variable-area nozzles 4 and 5 were determined under normal engine operating conditions (without afterburning) because the variable-area nozzle is in a more nearly closed position for this type of operation than it is under afterburning conditions and hence is operating with a more critical area ratio. Furthermore, because any loss in engine thrust that occurs during normal engine operating conditions is in effect during the entire flight of an airplane, this loss is of greater importance than thrust losses that may occur during relatively short periods of

augmented engine operation. Prior to conducting these performance runs, the mechanical reliability of nozzles 4 and 5 was determined under afterburning conditions.

In order to account for the variation in engine-inlet conditions between the series of runs with the variable-area and fixed-area exhaust nozzles, the data were corrected to standard sea-level conditions by the use of the conventional correction factors defined as:

$$\theta = \frac{\text{compressor-inlet total temperature}}{\text{NACA standard sea-level temperature}}$$

$$\delta = \frac{\text{compressor-inlet total pressure}}{\text{NACA standard sea-level pressure}}$$

The corrected engine performance parameters are:

F_j/δ corrected jet thrust, (lb)

$N/\sqrt{\theta}$ corrected engine speed, (rpm)

$\dfrac{W_a\sqrt{\theta}}{\delta}$ corrected air flow, (lb/sec)

$\dfrac{W_f}{F_j\sqrt{\theta}}$ corrected specific fuel consumption, (lb/(hr)(lb thrust))

$\dfrac{W_f}{\delta\sqrt{\theta}}$ corrected fuel flow, (lb/hr)

The performance of the various variable-area exhaust nozzles is evaluated by comparison of engine performance data obtained with both the variable-area nozzles and the fixed-area conical nozzles at the same engine operating conditions. Two different methods are used to make this comparison, the first method for all the nozzles and the second method for nozzles 3, 4, and 5. For the first method of comparison, the corrected jet thrust and fuel flow are plotted against the corrected engine speed to provide one set of curves for various sized fixed-area exhaust nozzles and a second set of curves for various positions of the variable-area exhaust nozzle. These sets of curves are then cross-plotted to obtain a final plot of

corrected jet thrust against corrected fuel flow at various con-
stant corrected engine speeds for both the fixed- and variable-area
exhaust nozzles. Because the jet thrust with both types of exhaust
nozzle are thus compared at the same engine speed, the two nozzles at
the same fuel flow are operating with the same inlet pressure and
temperature provided that the component efficiencies of the engine
have not changed between the two series of runs. The percentage
difference in thrust provided by the two exhaust nozzles at the
same fuel flow is therefore equal to the percentage difference in
nozzle velocity coefficient or the square root of the percentage
difference in nozzle efficiency. For the second method of com-
parison, the theoretical jet velocity defined as

$$V_t = \sqrt{2gJ\Delta H}$$

where

V_t theoretical jet velocity, (ft/sec)

g acceleration due to gravity, (ft/sec^2)

J mechanical equivalent of heat, ((ft)(lb)/Btu)

ΔH enthalpy drop across nozzle, (Btu/lb)

is plotted against the effective jet velocity defined as

$$V_e = \frac{F_j g}{(W_a + W_f)}$$

where

V_e effective jet velocity, (ft/sec)

F_j jet thrust, (lb)

W_a air flow, (lb/sec)

W_f fuel flow, (lb/sec)

The enthalpy drop ΔH was calculated from the measured nozzle-
inlet total temperature and pressure and the ambient nozzle-outlet

pressure with the aid of the thermodynamic data given in the tables
of reference 3. The advantage of this type of plot is that it pro-
vides a single correlation of data obtained for various engine speeds
and exhaust-nozzle sizes; all the test data may thus be used for
comparison purposes. Again, the percentage difference in the effec-
tive jet velocity for the two types of exhaust nozzle at the same
theoretical jet velocity (or enthalpy drop) is equal to the per-
centage difference in nozzle velocity coefficient or the square
root of the percentage difference in nozzle efficiency.

RESULTS AND DISCUSSION

The performance of the five different variable-area nozzles,
as determined from comparative performance obtained with conven-
tional fixed-area conical nozzles on three different turbojet
engines, is discussed. Additional performance data obtained with
nozzle 2 on the 4000-pound-thrust axial-flow-compressor engine are
also presented to illustrate the effect of varying the exhaust-
nozzle area on the engine thrust and specific fuel consumption.

Variable-Area Exhaust-Nozzle Performance

Nozzle 1. - A photograph of variable-area exhaust nozzle 1
installed on an engine tail pipe is shown in figure 3 and the
details of the construction of this nozzle are presented in fig-
ure 4. This nozzle consists essentially of a fixed inner section
having the shape of a spherical segment and two spherically shaped,
movable nozzle flaps. Both the fixed inner section and the movable
flaps of this nozzle are so made that the surfaces lie in con-
centric spheres, thus allowing relative motion between the flaps
and the inner section without changing the radial clearance between
them. A seal, which consisted of metal strips as shown in detail A
of figure 4, was incorporated between the flaps and the inner
nozzle to prevent leakage of gas.

The performance of this variable-area exhaust nozzle, which
was determined with the 1600-pound-thrust centrifugal-flow-compressor
engine, is summarized in figure 5 in which the corrected jet thrust
is plotted against the corrected fuel flow for several constant
engine speeds. The points obtained by cross-plotting the variable-
speed curves are coded for both the fixed-area conical nozzles and
the variable-area nozzle at engine speeds of 84.9, 90.9, 97.0, and
100 percent of rated speed. The results show that, within the
experimental error, there is no difference in the engine thrust,
and hence in the efficiency, of the fixed and variable-area exhaust
nozzles.

The metal sealing strips on the variable-area nozzle were apparently effective in preventing gas leakage. When operating at high gas temperatures, however, the metal seals would jam and the nozzle flaps could not be moved until the entire nozzle had been cooled. A more detailed description of this nozzle and the experimental investigation of its performance is reported in reference 1.

Nozzle 2. - Variable-area nozzle 2, shown in the photographs of figure 6 and the detailed drawing in figure 7, was similar to nozzle 1 in general design features. Metal sealing strips were also installed on this nozzle but immediate difficulty was experienced with jammed flaps; consequently, the strips were bent back to provide ample clearance (1/16 to 1/4 in.) and therefore did not serve as seals during the investigation. The outlet plane of this nozzle in the wide-open position was slightly curved as shown in figure 6(b). The projected area of the nozzle outlet was circular in an intermediate nozzle position and elliptical in both the closed and open position with the major axes of these two ellipses normal to each other.

The performance of this variable-area exhaust nozzle, which was obtained with the 4000-pound-thrust axial-flow-compressor engine, is shown in figure 8 in which the corrected jet thrust is plotted against the corrected fuel flow for several constant engine speeds. The jet thrust obtained at high values of fuel flow with the variable-area nozzle (closed position) is about $2\frac{1}{2}$ percent lower than the thrust obtained with the fixed-area nozzles. This difference in thrust corresponds to a difference in nozzle velocity coefficient of $2\frac{1}{2}$ percent and a difference in nozzle efficiency of about 5 percent. As the variable-area nozzle is opened (decreased fuel flow) the difference in thrust decreases until with the nozzle flaps wide open the thrusts are equal.

In order to investigate the effect of gas leakage under the movable flaps, the nozzle was partly closed and the space between the movable flaps and the fixed inner section was packed with wet asbestos to eliminate the leakage. The results of a series of runs with the flaps packed in this manner are shown by the data points in figure 8. This elimination of gas leakage under the movable flaps reduced the thrust loss from $2\frac{1}{2}$ to 1 percent and it may therefore be concluded that a large portion of the original thrust loss was due to leakage.

This nozzle was used for about 50 hours and operated satisfactorily during the entire investigation. A relatively unimportant

failure of a hinge pin that occurred was corrected by increasing
the pin diameter from 1/4 to 3/8 inch.

Nozzle 3. - Variable-area nozzle 3, illustrated in figures 9
and 10, incorporated the straight tail pipe as the fixed inner
section, which eliminated the necessity of a spherical segment on
the end of the tail pipe and provided the maximum area possible in
the wide-open position. The seal design was changed to the type
shown in the detail of figure 10 to avoid the jamming of the flaps
that occurred with the seal used with nozzles 1 and 2. Two rings
were welded to the outer wall of the inner section to form a con-
tinuous channel. A ring of braided Inconel was inserted in this
channel and held against the inner surface of the flaps by both a
spring and gas pressure that was transmitted to the space beneath
the ring of braided Inconel through holes drilled in the pipe wall.

The performance of variable-area nozzle 3, which was deter-
mined with the 4000-pound-thrust centrifugal-compressor engine,
is shown in figure 11 in which the corrected jet thrust is plotted
against the corrected fuel flow for several engine speeds. The
thrust with the variable-area nozzle at the various positions
investigated (various engine fuel flows) and at the three different
engine speeds was about 5 percent less than that with the fixed
nozzle, which corresponds to a 5-percent loss in velocity coef-
ficient and a 10-percent loss in nozzle efficiency. A run was also
made with the nozzle packed with wet asbestos to check the effec-
tiveness of the seal. The results, illustrated by the data points
in figure 11, show that the thrust loss was not regained and that
the seal was apparently effective in preventing gas leakage. Con-
trary to the results obtained with nozzle 2, these thrust losses
are not due to gas leakage.

As indicated in the table of nozzle characteristics previously
presented, the ratio a/b of the projected outlet area is somewhat
greater for nozzle 3 than for nozzle 2 and nozzle 3 has a somewhat
higher ratio of transverse to longitudinal projected outlet area A/B,
and hence a more nonplanar outlet configuration, than nozzle 2. The
larger thrust loss of nozzle 3 compared to that of nozzle 2 may
therefore be attributed to either or both of these design features
although, as will be subsequently illustrated, the effect of the
shape of the outlet ellipse is of secondary importance. The nature
of the velocity, temperature, and pressure gradients at the nozzle
inlet may also influence the nozzle efficiency so that results
obtained with one engine are not directly applicable to those with
another engine of different design.

The performance of variable-area nozzle 3 is also compared
with the various fixed-area nozzles in figure 12 in which the effec-
tive jet velocity is plotted against the theoretical jet velocity.
This plot correlates all the data obtained for the range of engine
speeds and nozzle-outlet areas investigated. The results, which
are in satisfactory agreement with the results of figure 11, show
that a loss in thrust of about 4 percent occurred for all operating
conditions. The values of the effective jet velocity of the various
fixed-area nozzles are slightly higher than the computed values of
the theoretical jet velocity. This anomaly is attributed to the
probability that the calculated enthalpy drop ΔH is not equal to
the actual enthalpy drop because of the limited amount of instru-
mentation used to measure the average nozzle-inlet temperature and
pressure. Although it is therefore evident that an accurate measure
of the absolute nozzle efficiency was not obtained, the comparison
of the variable- and fixed-area nozzles is probably accurate because
the same instrumentation was used for both sets of comparative per-
formance data.

No mechanical difficulties were encountered with this nozzle.

Nozzles 4 and 5. - Variable-area exhaust nozzles 4 and 5 differ
from those previously investigated in that they are designed for
installation on an engine with an afterburner and consequently had
a larger pipe section and a much larger area change from the closed
position to the open position.

Nozzle 4, illustrated in figures 13 and 14, was designed and
fabricated by an engine manufacturer for a larger engine and was
modified for this investigation by extending the lips of the two
movable flaps about 2 inches. This nozzle has metal sealing strips
between the flaps and the inner section patterned after that used
with nozzle 1. A cooling shroud was built into the inner wall.

Nozzle 5, illustrated in figures 15 and 16, was designed to
avoid an extremely nonplanar outlet configuration and to maintain
the outlet area as nearly circular as possible for all positions
of the nozzle flaps. These objectives were accomplished by a design
similar to that of nozzle 2 with a circular outlet area at an inter-
mediate nozzle position and an elliptical area in both the fully
open and fully closed position with their major axes normal to each
other. One of the movable flaps of this nozzle incorporated two
circular side flaps or spherical segments centered around the two
pivot shafts of the nozzle over which the other flap rotated. These
spherical side segments filled the gap that otherwise would have been
present between the two flaps with the nozzle in the open position.

As shown in the detail of figure 16, the nozzle incorporated a seal of braided Inconel similar to the seal used for nozzle 3.

The performance of these two variable-area nozzles, which was determined on the 4000-pound-thrust axial-flow-compressor engine and afterburner tail pipe, is shown in figure 17 in which the corrected jet thrust is plotted against the corrected fuel flow for engine speeds of 80, 90, and 100 percent of rated speed. The data were obtained with normal (nonafterburning) operation of the engine and the nozzle position was varied from fully closed to about three-eighths open for nozzle 4 and from fully closed to about one-quarter open for nozzle 5. For all the conditions investigated, the thrust with nozzle 4 is from 5 to 8 percent lower than that of the fixed-area nozzles and the thrust with nozzle 5 is nearly the same as that with the fixed-area nozzles.

The performance of variable-area nozzles 4 and 5 are further compared with that of the fixed-area nozzles in figure 18 by a plot of effective jet velocity against the theoretical jet velocity. Correlated on this plot are data for the entire range of engine speeds and nozzle-outlet areas investigated. For all the conditions investigated, the thrust with nozzle 4 was about 8 percent less than with the fixed-area nozzles and the thrust with nozzle 5 was about $1\frac{1}{2}$ percent less than with the fixed-area nozzles. These thrust losses with variable-area nozzles 4 and 5 correspond to losses in nozzle velocity coefficient of about 8 and $1\frac{1}{2}$ percent, respectively, and losses in nozzle efficiency of about 15 and 3 percent, respectively. The greater losses of nozzle 4 compared with those of nozzle 5 are believed to be primarily due to the greater ratio of transverse to longitudinal projected outlet area (nonplanar outlet) for this nozzle. As previously indicated, this area ratio A/B for nozzle 4 is 0.25 as compared with a value of 0.06, the smallest of all the nozzles investigated, for nozzle 5. The extremely narrow ellipse of the outlet area of nozzle 4 and the presence of the inner cooling shroud may also have contributed to losses in jet thrust. The effect of outlet-area shape on the nozzle efficiency, however, is apparently of secondary importance compared with the effect of nonplanar outlet configuration because the ellipse of the outlet area of nozzle 5, which had a thrust loss of only $1\frac{1}{2}$ percent, was about the same as that of nozzle 3, which had a thrust loss of 4 to 5 percent.

A comparison of the data of figure 18 with the data of figure 12 indicates that for the same theoretical jet velocity the

effective jet velocity of the two sets of fixed-area nozzles dif-
fered by 6 to 7 percent. This apparent difference in effective jet
velocity of the two sets of fixed-area nozzles is attributed to
inaccuracies in measuring the actual enthalpy drop across the nozzle
because of the different arrangement and limited amount of instru-
mentation used. As previously discussed, these inaccuracies of
measurement of exhaust-nozzle enthalpy drop do not affect the
accuracy of the comparison of the fixed- and variable-area exhaust
nozzles because the same instrumentation was used for each nozzle
investigation.

During the investigation of the mechanical reliability of these
nozzles under afterburning conditions, nozzle 4 warped severely and
jammed after about 10 minutes of operation. The complete nozzle had
to be rebuilt to restore its operation and to obtain the performance
data presented. Nozzle 5 warped slightly out of shape after about
40 minutes of continuous afterburner operation over a range of tail-
pipe outlet temperatures up to about 3000° R but remained operative
and was satisfactorily used for the performance investigation
reported.

Summary of variable-area nozzle performance. - The various
design features of this type of variable-area nozzle that may con-
tribute to thrust losses cannot be isolated and evaluated from the
results of these investigations because of nonsimilarity among the
various nozzles in such features as the elliptical shape of the
outlet area, the shape of the transverse projected outlet area A,
the area ratio of the nozzles, and the presence of an inner cooling
shroud in one of the nozzles. As previously discussed, however,
the principal feature of design that contributes to a loss in thrust
is believed to be the nonplanar outlet configuration formed by the
edges of the two movable nozzle flaps and associated spillage of
the exhaust jet normal to the engine axis. The performance of the
five variable-area nozzles are accordingly summarized in figure 19
as a plot of the percentage loss in thrust of the variable-area
nozzles at rated engine conditions relative to the performance of
the fixed-area conical nozzles against the ratio of transverse to
longitudinal projected outlet area A/B. It should be recognized
that the area ratio A/B is only an approximate index of the spill-
age of flow normal to the engine axis because the shape of the
area A may also be an important factor. Although the data points
scatter somewhat in the region of low values of A/B, a single
curve that illustrates a rapid increase in thrust loss with increas-
ing area ratio A/B has been drawn through the data. Although the
results represented by this curve are of a qualitative nature, it
is apparent that the area ratio A/B must be kept small in order
to minimize losses in engine thrust.

Engine Performance with Nozzle Adjustment

The effect of varying the area of the exhaust nozzle on the
specific fuel consumption and thrust of a turbojet engine is pre-
sented in order to illustrate the gains in engine performance
possible by the use of a variable-area exhaust nozzle. The data
were obtained on a 4000-pound-thrust axial-flow-compressor engine
at zero-ram sea-level conditions using variable-area nozzle 2. The
changes in engine performance due to variations in exhaust-nozzle
area are dependent on both the type of engine and the simulated
flight operating conditions. The results presented are therefore
quantitatively applicable only to the type of engine and exhaust
nozzle used and are primarily presented to illustrate the effects
of nozzle adjustment in a qualitative manner.

The variation in corrected jet thrust with engine speed for
various positions of the variable-area nozzle from fully closed to
fully open is shown in figure 20. The ratio of the outlet area of
the nozzle in the wide-open position to that in the closed position
is 1.31. Engine operation with the fully closed nozzle was limited
to a speed of about 90 percent of the rated value because of tail-
pipe gas-temperature limitations. At rated engine speed, an increase
in nozzle area from the one-third-open position to the fully open
position, or an area change of about 20 percent, decreased the thrust
from 3880 to 2590 pounds. A range of thrust regulation of about
33 percent was therefore obtained at constant engine speed by this
adjustment of the exhaust-nozzle area.

The effect of varying the exhaust-nozzle area on the specific
fuel consumption is shown for several engine speeds in figure 21 in
which the corrected specific fuel consumption is plotted against the
corrected jet thrust. For these data, the thrust with the variable-
area nozzle was increased from 0 percent in the open position to
$1\frac{1}{2}$ percent in the closed position to adjust for the losses due to
gas leakage under the flaps, as previously discussed. The solid
curves are obtained by varying the area of the exhaust nozzle
(increasing area with decreasing thrust) at various constant engine
speeds and the dashed curve represents engine performance with the
conventional fixed-area exhaust nozzle and is obtained by varying
the engine speed. The specific fuel consumption of the engine with
the fixed-area exhaust nozzle is a minimum at a thrust of about
3500 pounds (about 88 percent of rated thrust) and increases con-
tinuously as the thrust (and engine speed) is reduced below this
value. With the variable-area nozzle, however, a family of curves
is obtained by varying the exhaust-nozzle area at various constant

engine speeds. The envelope of this family of curves represents the optimum conditions of engine speed and nozzle size for minimum specific fuel consumption. If, for example, a thrust of 2500 pounds (about 65 percent of rated thrust) is desired, operation at from 95- to 100-percent rated engine speed and increased exhaust-nozzle area (decreased gas temperature) results in a specific fuel consumption of 1.025 pounds per hour per pound of thrust as compared to 1.085 with the fixed-area exhaust nozzle and at reduced engine speed. A reduction in specific fuel consumption of 6 percent is therefore possible at this engine-thrust output by the use of the variable-area exhaust nozzle.

SUMMARY OF RESULTS

From a comparison and study of the results of several investigations of the performance of different types of clamshell variable-area exhaust nozzle, which have been conducted on several full-scale turbojet engines at zero-ram sea-level conditions, this type of variable-area exhaust nozzle was found to have satisfactory mechanical reliability even after operating under afterburning conditions for about 40 minutes. With three of the variable-area exhaust nozzles investigated, one of which provided an area variation of about 1.86 to 1.00, the engine thrust was within 0 to $1\frac{1}{2}$ percent of that obtained with fixed-area nozzles. The other two variable-area nozzles investigated resulted in thrust losses of from 4 to 8 percent. The cause of the higher thrust loss of these two nozzles is principally attributed to a nonplanar outlet configuration formed by the angle between the edges of the nozzle flaps when the nozzle was in a closed position. The nozzle having the highest thrust loss also incorporated an inner cooling shroud and had an extremely narrow ellipse for the projected outlet area in the closed position, both of which may also have contributed to thrust losses. Leakage of exhaust gases under the nozzle flaps, which was found to cause a thrust loss of $1\frac{1}{2}$ percent with one of the nozzles, was satisfactorily eliminated in other nozzles by including sealing devices in the nozzle. During one of the nozzle investigations, a range of thrust regulation at constant engine speed of 33 percent was obtained by a 20-percent variation in the exhaust-nozzle area. At a thrust output of 65 percent of the rated value, a reduction in specific fuel consumption of 6 percent below that obtained with the normal fixed-area nozzle was obtained by means of the variable-area exhaust nozzle.

Lewis Flight Propulsion Laboratory,
    National Advisory Committee for Aeronautics,
        Cleveland, Ohio.

REFERENCES

1. Wilcox, E. C.: Tests of an Adjustable-Area Exhaust Nozzle for Jet-Propulsion Engines. NACA MR No. E5H16, 1945.

2. Wallner, Lewis E.: Investigation of Performance of Turbojet Engine with Constant- and Variable-Area Exhaust Nozzles. NACA RM No. E8J25d, 1948.

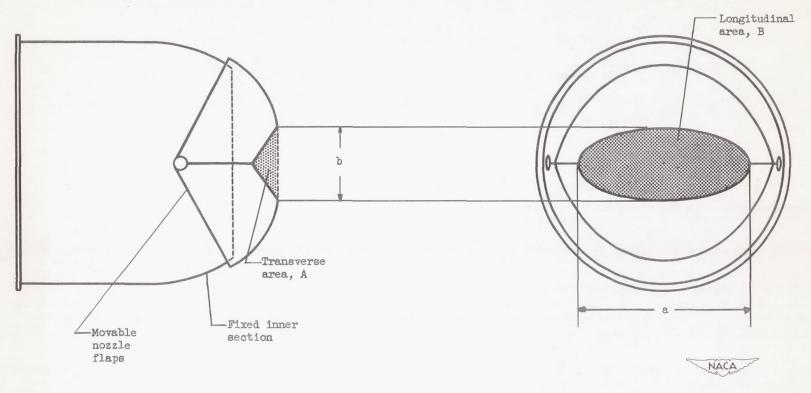3. Keenan, Joseph H., and Kaye, Joseph: Thermodynamic Properties of Air. John Wiley & Sons, Inc., 1945.

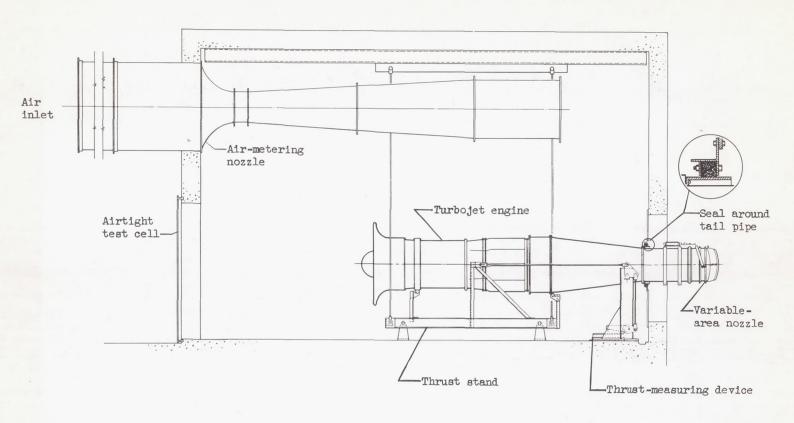Figure 1. - Schematic diagram of clamshell variable-area exhaust nozzle in closed position.

Figure 2. - Typical installation of turbojet engine for zero-ram sea-level performance investigations.

Air inlet

Air-metering nozzle

Airtight test cell

Turbojet engine

Seal around tail pipe

Variable-area nozzle

Thrust stand

Thrust-measuring device

NACA
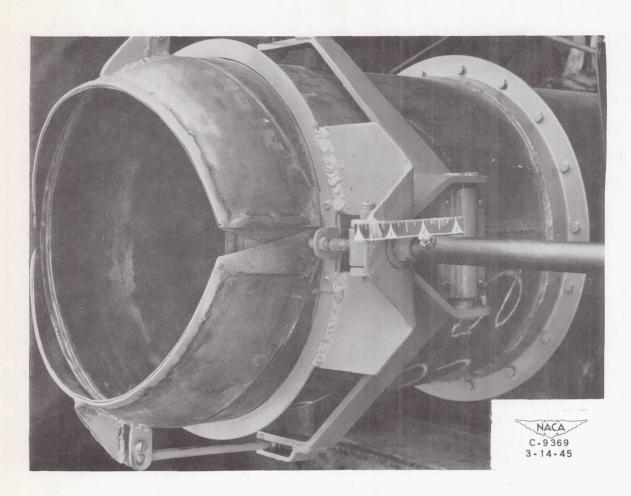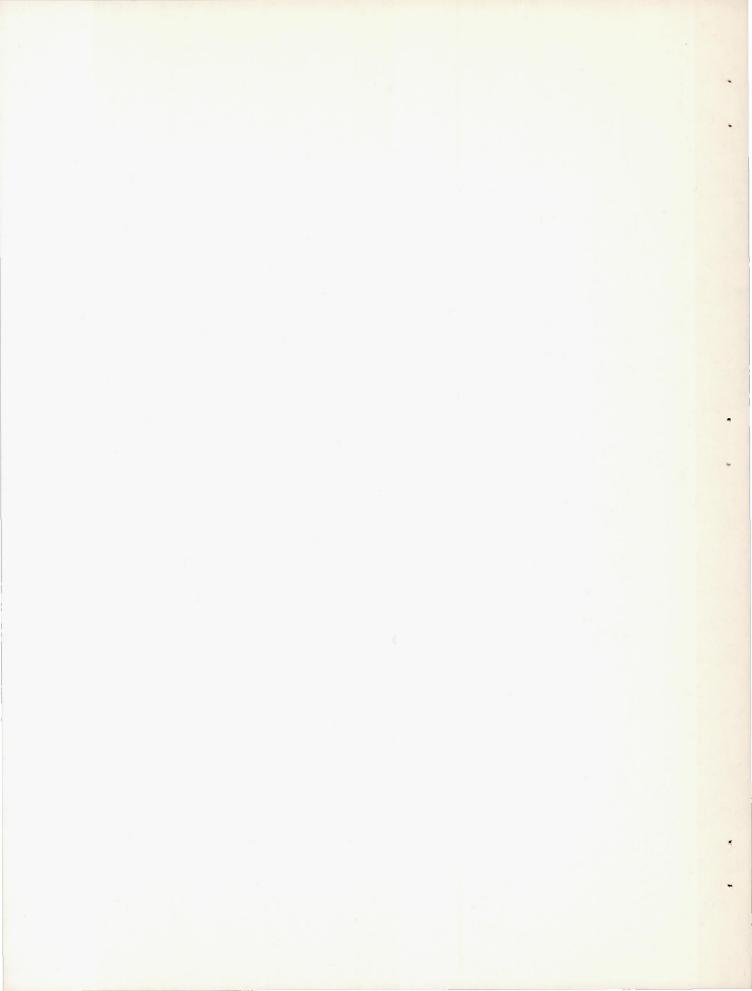
Figure 3. - Variable-area nozzle 1 installed on engine tail pipe.

Detail A

$\frac{1}{16}$"

Movable nozzle flap

Thin metal sealing
strip welded to
movable nozzle flap

Thin metal sealing strip
welded to inner nozzle

Fixed
pivot
pin

Bell crank

Adjusting
screw

Detail A

Open

Closed

13"

$10\frac{1}{2}$"

$14\frac{1}{4}$"

Movable nozzle flap

Bell crank

Link for moving nozzle flap

$12\frac{5}{8}$"
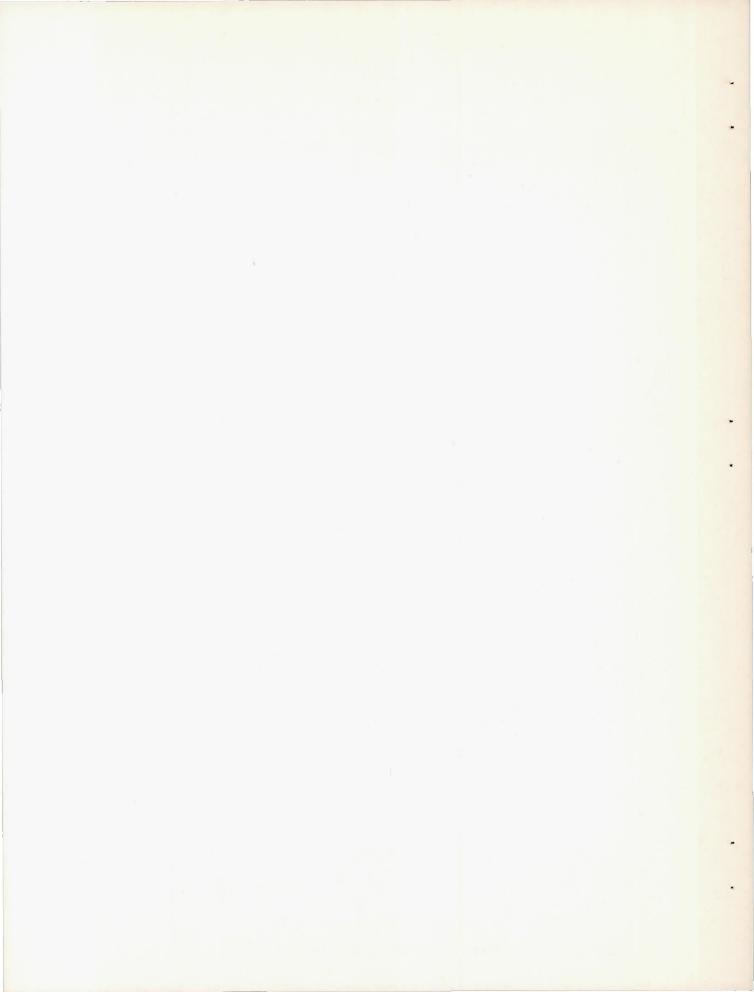
13"

NACA
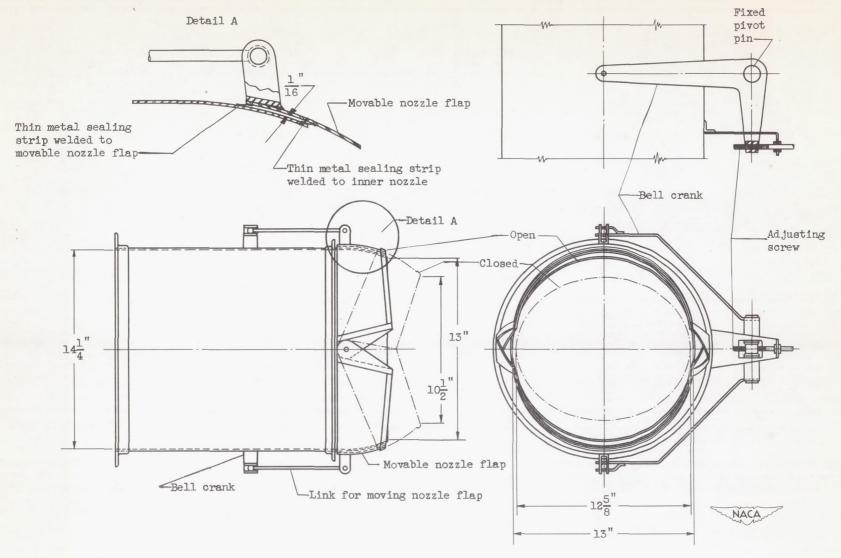
Figure 4. - Details of variable-area nozzle 1.
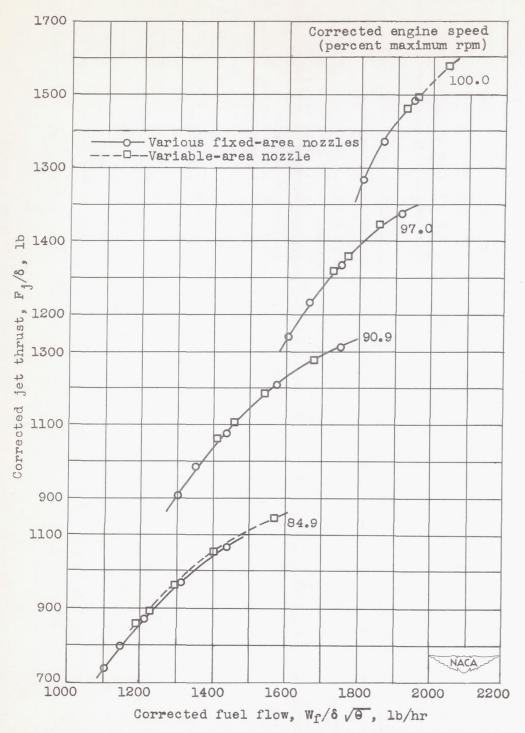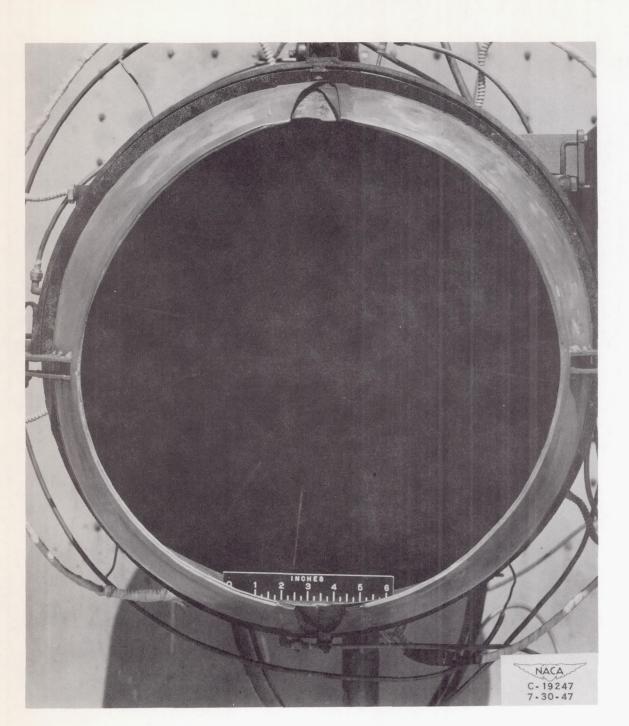
Figure 5. - Variation of corrected jet thrust with corrected
fuel flow for variable-area nozzle 1 and various fixed-area
nozzles at several engine speeds. (Figure taken from re-
ference 1.)

(a) End view; partly closed position.
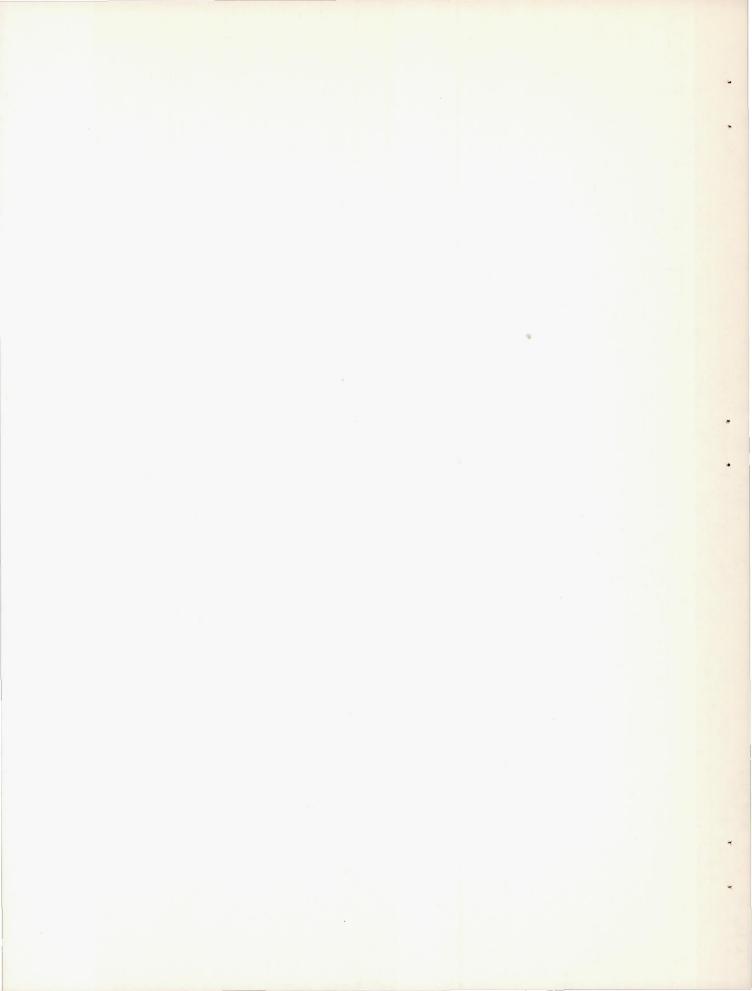
Figure 6. - Variable-area nozzle 2.

(b) Side view; wide-open position.

Figure 6. - Concluded. Variable-area nozzle 2.

Detail A

Movable nozzle flap

Inner nozzle

Metal sealing strips

Detail A

Open

Closed

21"

$15\frac{3}{8}$" $19\frac{7}{8}$"

Yoke and linkage for moving nozzle flaps

$17\frac{9}{16}$"

$18\frac{1}{8}$"

NACA
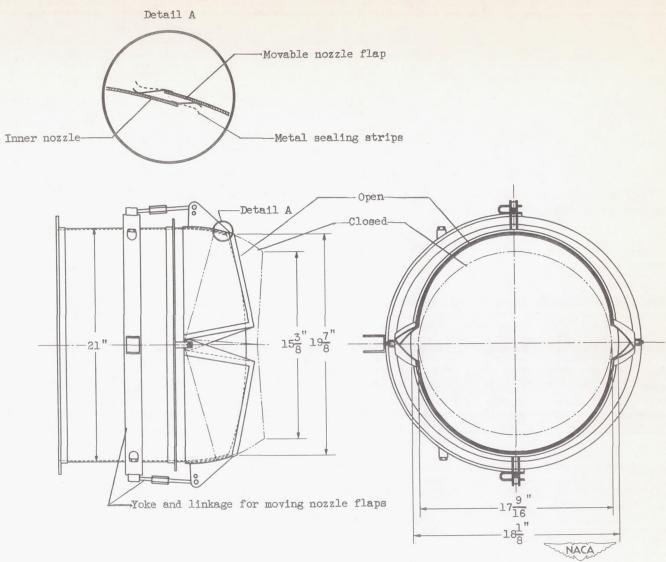
Figure 7. - Details of variable-area nozzle 2.
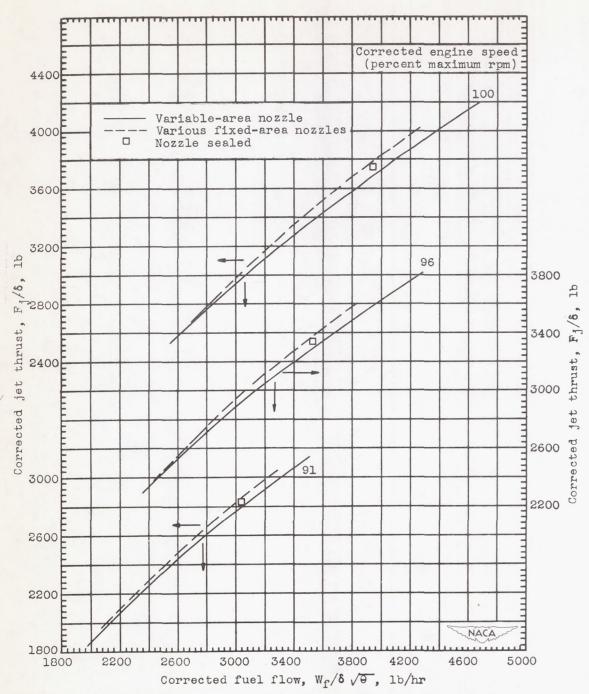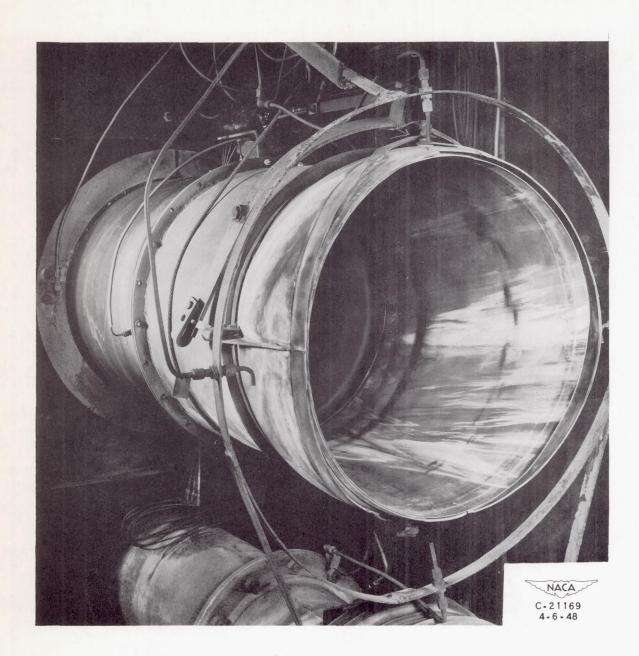
Figure 8. - Variation of corrected jet thrust with corrected fuel flow
for variable-area nozzle 2 and various fixed-area nozzles at several
engine speeds.

(a) Closed position.
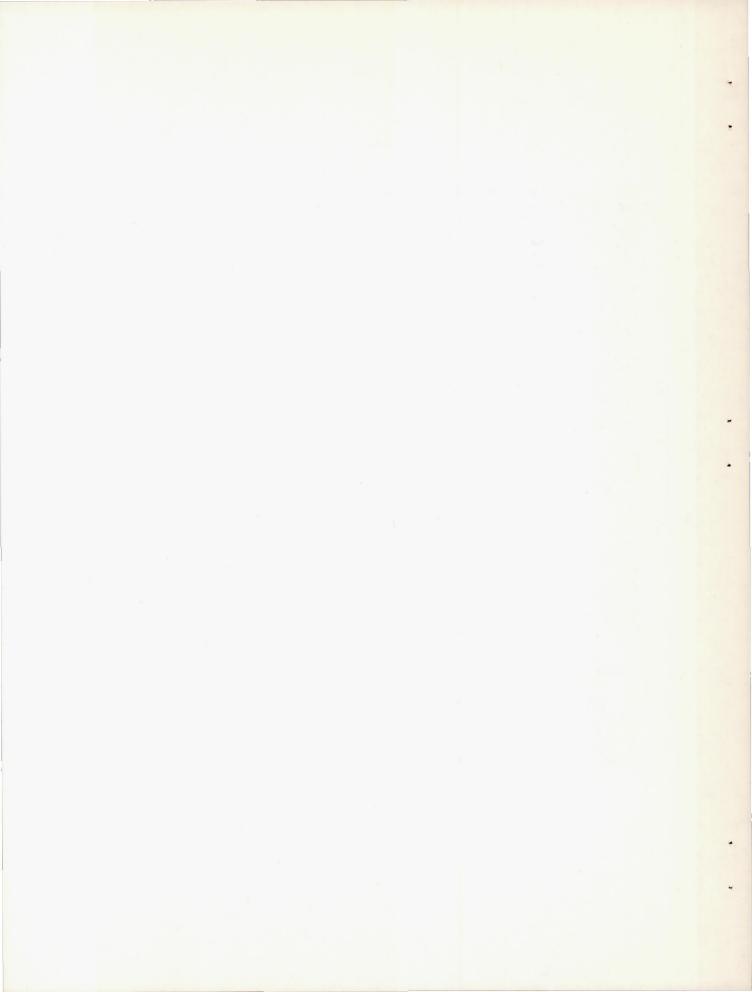
Figure 9. - Variable-area nozzle 3.

(b) Wide-open position.

Figure 9. - Concluded. Variable-area nozzle 3.

Detail A

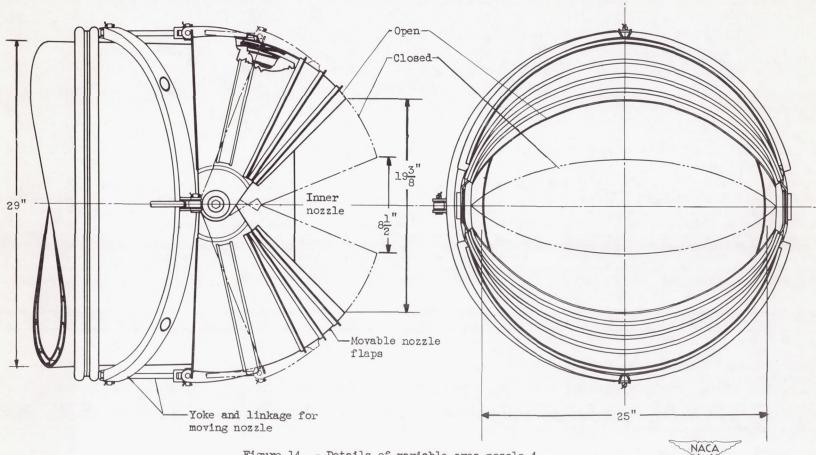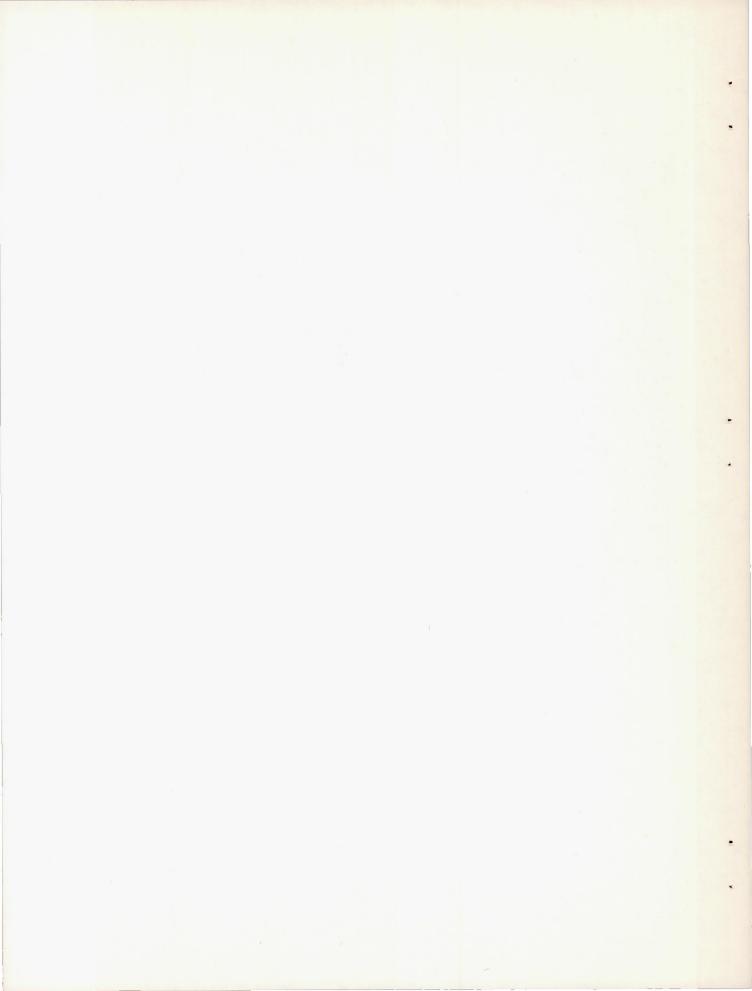Inconel braid

Movable nozzle flap

Spring

Orifices

21"

21"

$15\frac{1}{2}"$

Open

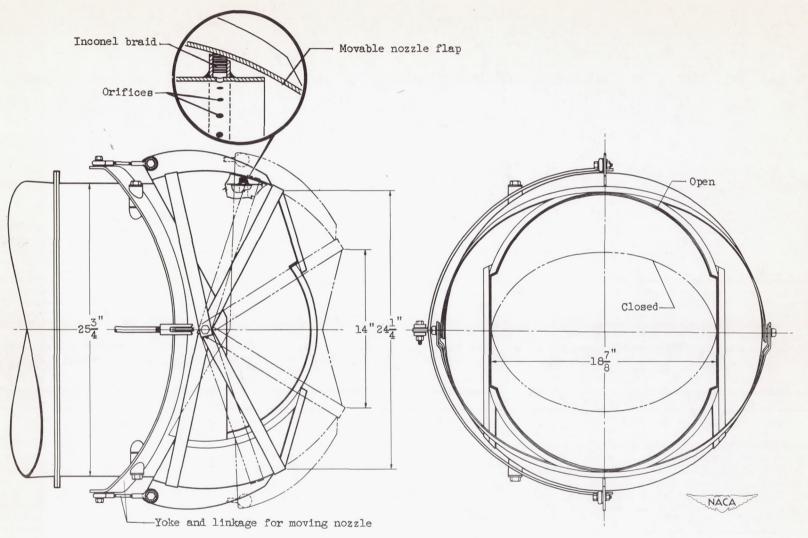Closed

Yoke and linkage for moving nozzle flaps

21"

NACA
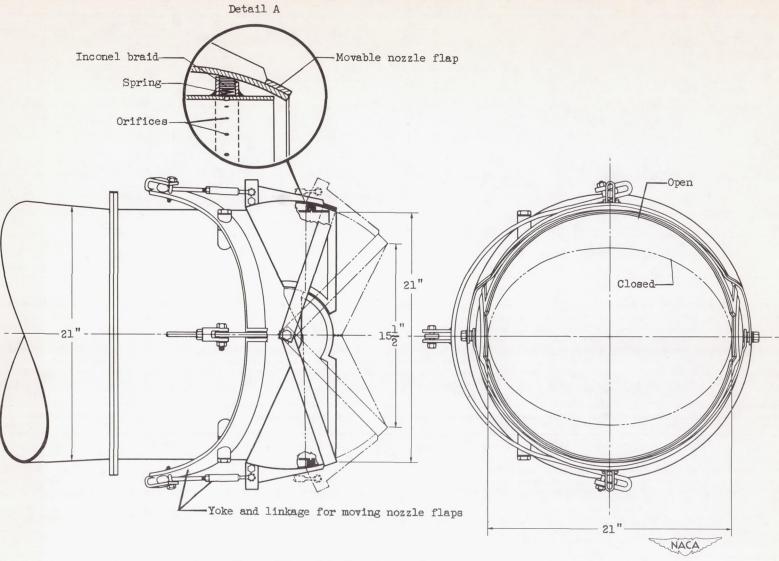
Figure 10. - Details of variable-area nozzle 3.
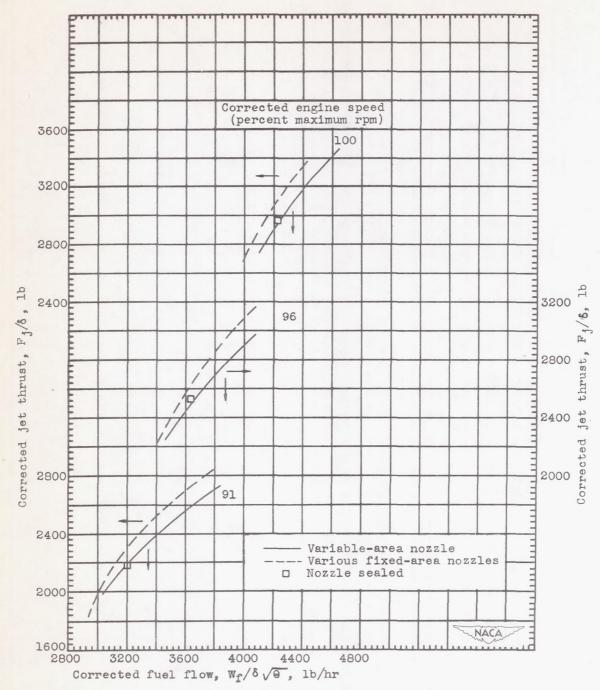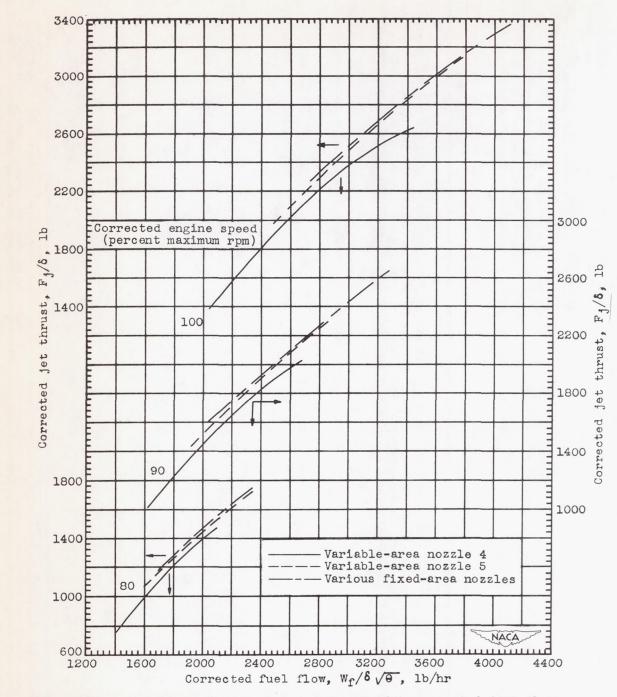
Figure 11. - Variation of corrected jet thrust with corrected fuel
flow for variable-area nozzle 3 and various fixed-area nozzles at
several engine speeds.

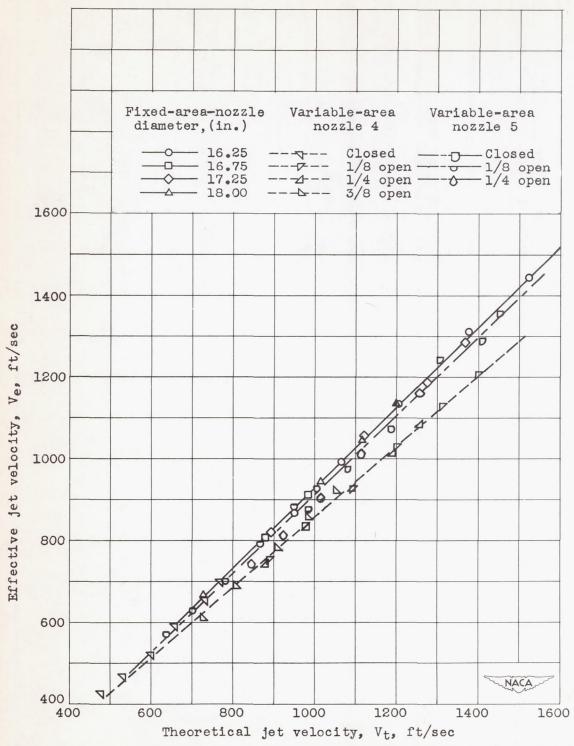Figure 12. - Comparison of effective jet velocity with variable-area
nozzle 3 and various fixed-area nozzles.

(a) Closed position.
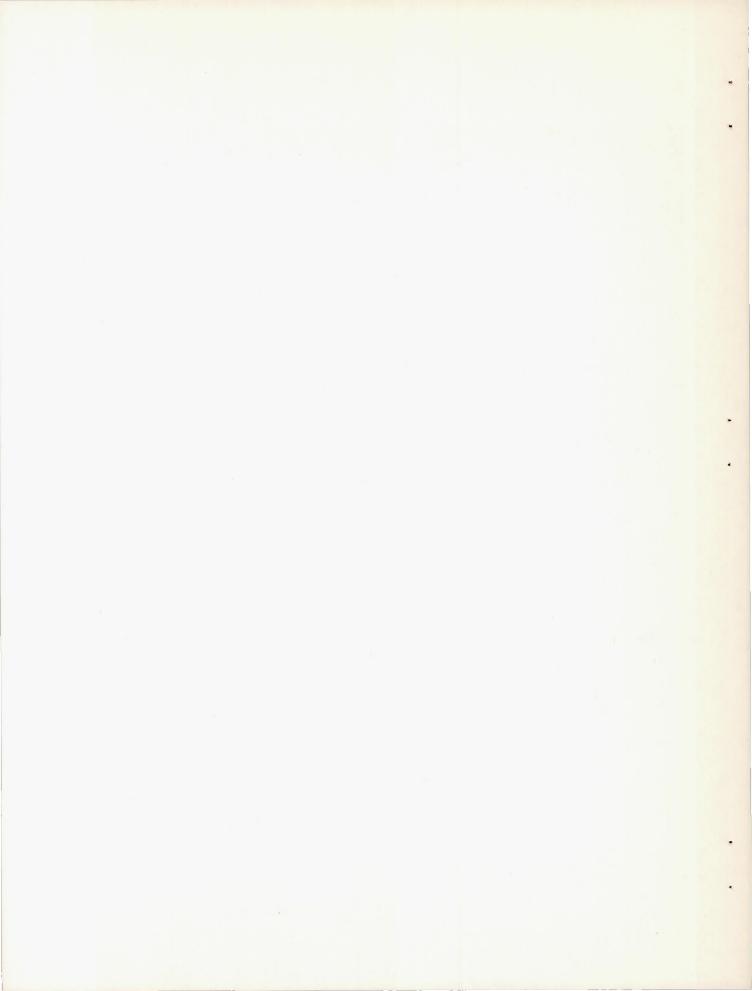
Figure 13. - Variable-area nozzle 4.

(b) Open position.

Figure 13. - Concluded. Variable-area nozzle 4.

Open

Closed

$19\frac{3}{8}$"

$8\frac{1}{2}$"

Inner
nozzle

Movable nozzle
flaps

Yoke and linkage for
moving nozzle

29"

25"

Figure 14. - Details of variable-area nozzle 4.

NACA

(a) Nearly closed position.
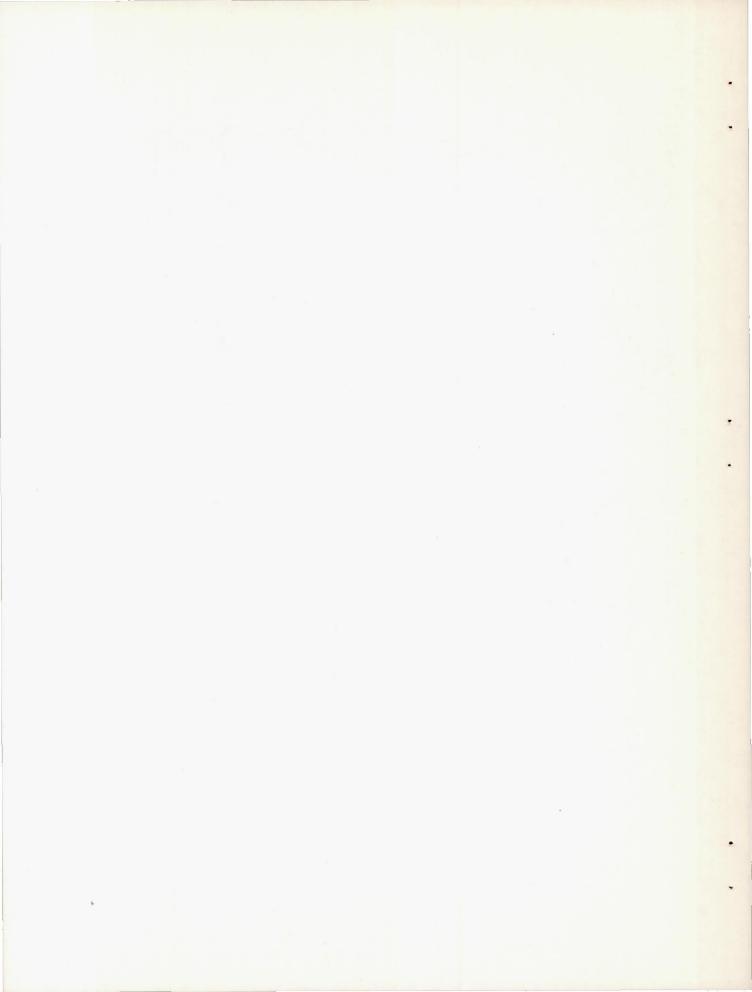
Figure 15. - Variable-area nozzle 5.

(b) Open position.

Figure 15. - Concluded. Variable-area nozzle 5.

Inconel braid

Movable nozzle flap

Orifices

Open

Closed

$25\frac{3}{4}"$

$14"$ $24\frac{1}{4}"$

$18\frac{7}{8}"$

Yoke and linkage for moving nozzle

NACA

Figure 16. – Details of variable-area nozzle 5.

Figure 17. - Variation of corrected jet thrust with corrected fuel flow
   for variable-area nozzles 4 and 5   and various fixed-area nozzles at
   several engine speeds.

Figure 18. - Comparison of effective jet velocity with variable-area
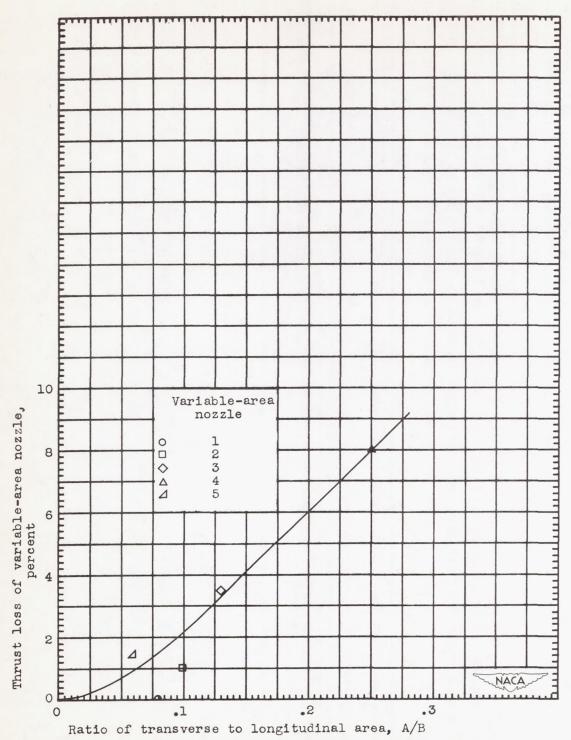nozzles 4 and 5 and various fixed-area nozzles.

Figure 19. - Variation of thrust loss of variable-area nozzle at rated
    engine conditions with ratio of transverse to longitudinal projected
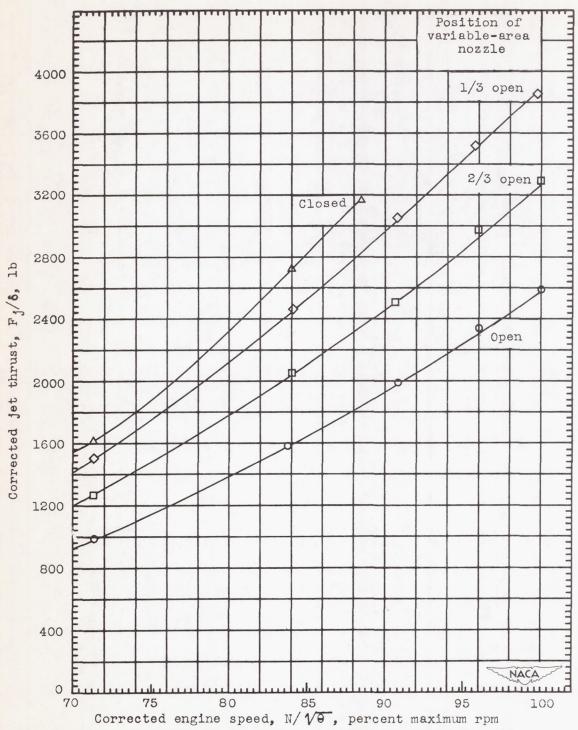   outlet area A/B.

Figure 20. - Variation of corrected jet thrust with corrected engine
   speed for variable-area nozzle in various positions. Axial-flow
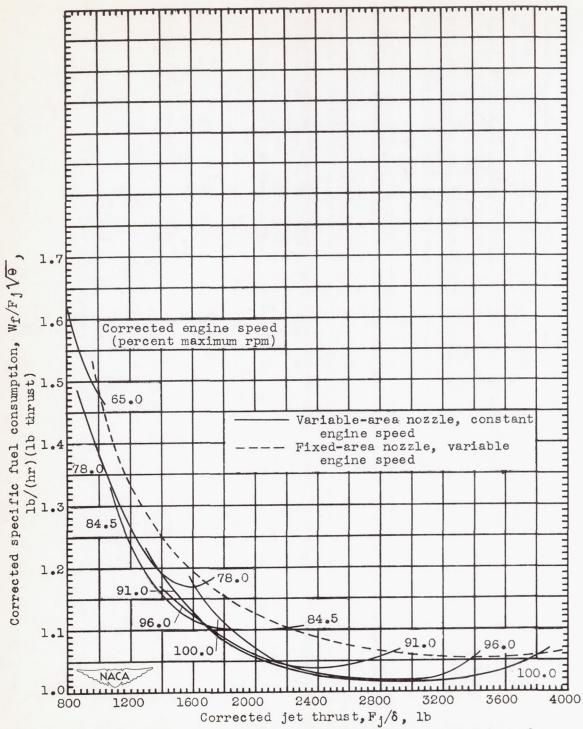   turbojet engine at zero-ram sea-level conditions.

Figure 21. - Comparison of corrected specific fuel consumption of an axial-flow turbojet engine at zero-ram sea-level conditions with fixed- and variable-area nozzles.